Flux Density Measurement for Industrial-Scale Solar Power Towers Using the Reflection off the Absorber

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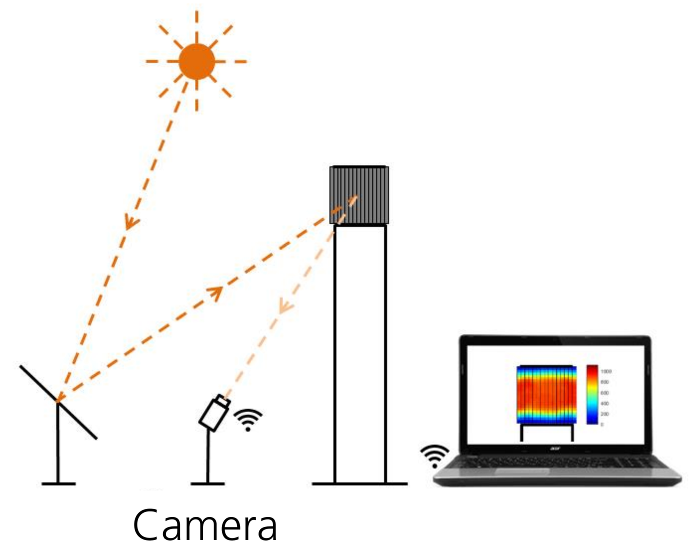
Motivation

- Flux density measurement is precious for
  - Heliostat control for optimized efficiency
  - Damage prevention & life time extension
  - Separate determination of heliostat field's and receiver's energy conversion efficiencies (in acceptance tests etc.)
- "Moving bar"-method suffers from high costs & effort due to moving parts under irradiation [1]
- Measurement method using the reflection off the absorber is not yet mature.

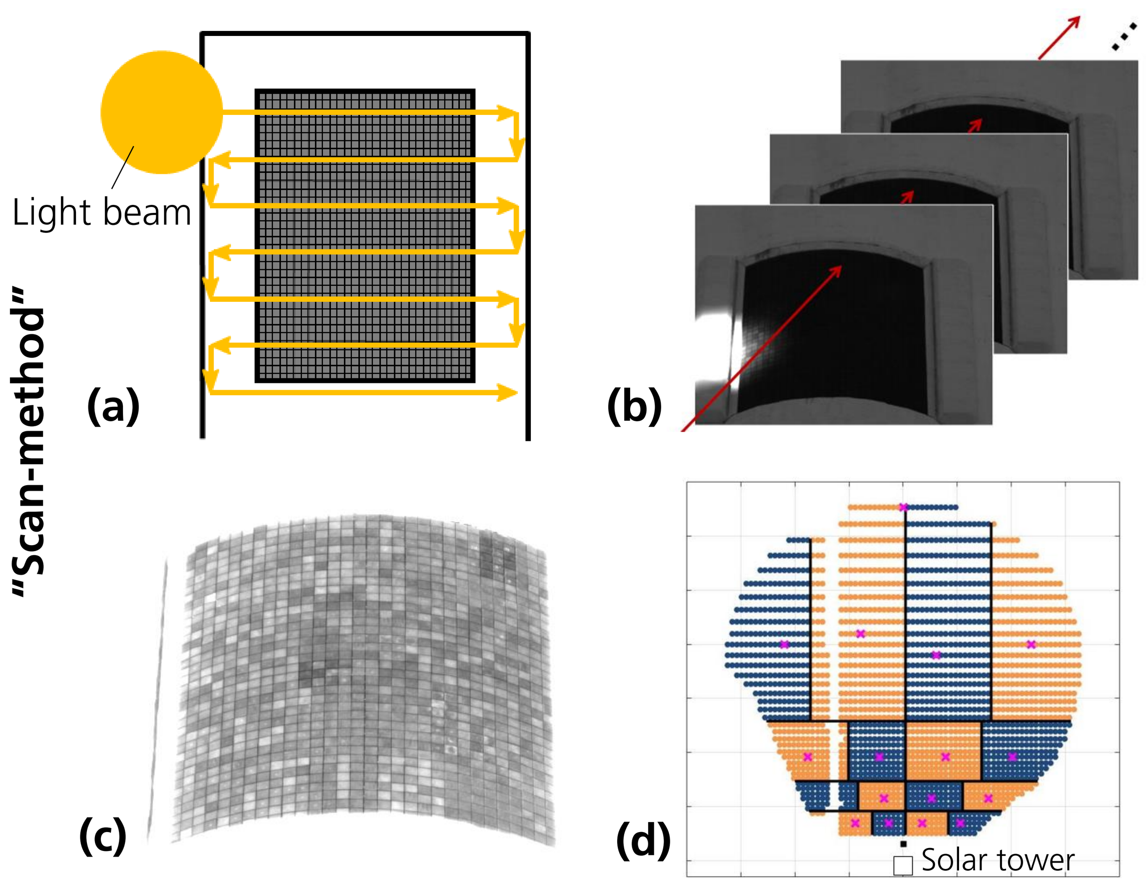
Objectives



General setup

- Improvement and assessment of flux density measurement using the reflection off the absorber [2]
- Investigation of the method's applicability to different receiver types
- Main challenges:
  1) Detection of absorber's **reflection properties** (in particular dependent on place / material and directions), status quo unsatisfactory
  2) Determination of **directional composition** of irradiation
  3) **Calibration** (image gray values ⇒ flux density values)

Approach & Methods



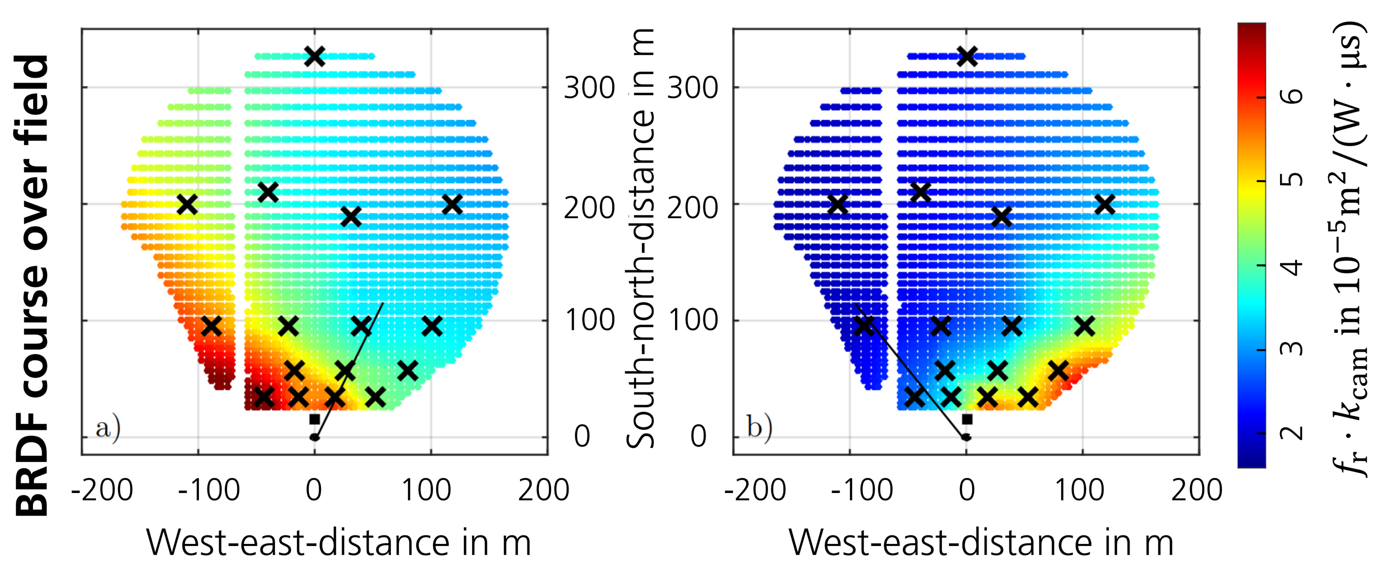
- Mathematical analysis of measurement method for external receivers (valid for open volumetric & tube receivers)

$$E_{i,\Omega,\lambda} \cdot d\Omega \cdot d\lambda \cdot f_{r,i}(\theta,\varphi,\lambda,T) \cdot k_{cam}(\lambda) \cdot t_{exp} = d^2 g_i \quad \Rightarrow \cdots \Rightarrow \quad E_i = g_i \cdot \underbrace{\frac{1}{\sum_j x_{i,j} \cdot \frac{f_{r,i,j,ef}(T)}{\bar{f}_r}}}_{\text{"correction"}} \cdot \underbrace{\frac{1}{k_{cam,ef} \cdot \bar{f}_r \cdot \bar{t}_{exp}}}_{\text{"calibration"}} \cdot \frac{\bar{t}_{exp}}{t_{exp}}$$

- Invention of patented **"scan method"** for improved detection of absorber's reflection properties. [3], [4]
  Tests at Solar Tower Juelich with open volumetric receiver.
  a) Movement of light beam on tight meander-shaped path. Usage of heliostat (daytime) or spotlight (nighttime). At the same time acquisition of image series (Juelich: 17 fps, approx. 10,000 images).
  b) Merging image series into single "maximum image" by determining maximum gray value pixel by pixel
  c) Maximum image equals hypothetical image taken during homogeneous irradiation of whole absorber surface with E_{max} at the same time. ⇒ Reflection properties are revealed!
  d) Detection of directional dependence: Division of heliostat field into 16 areas and conduction of scan method from one place per area
  ⇒ Application of scan results for reflectance correction of raw images (see section Results)
- Conduction of innovative methods for determination of radiation's directional composition and for calibration

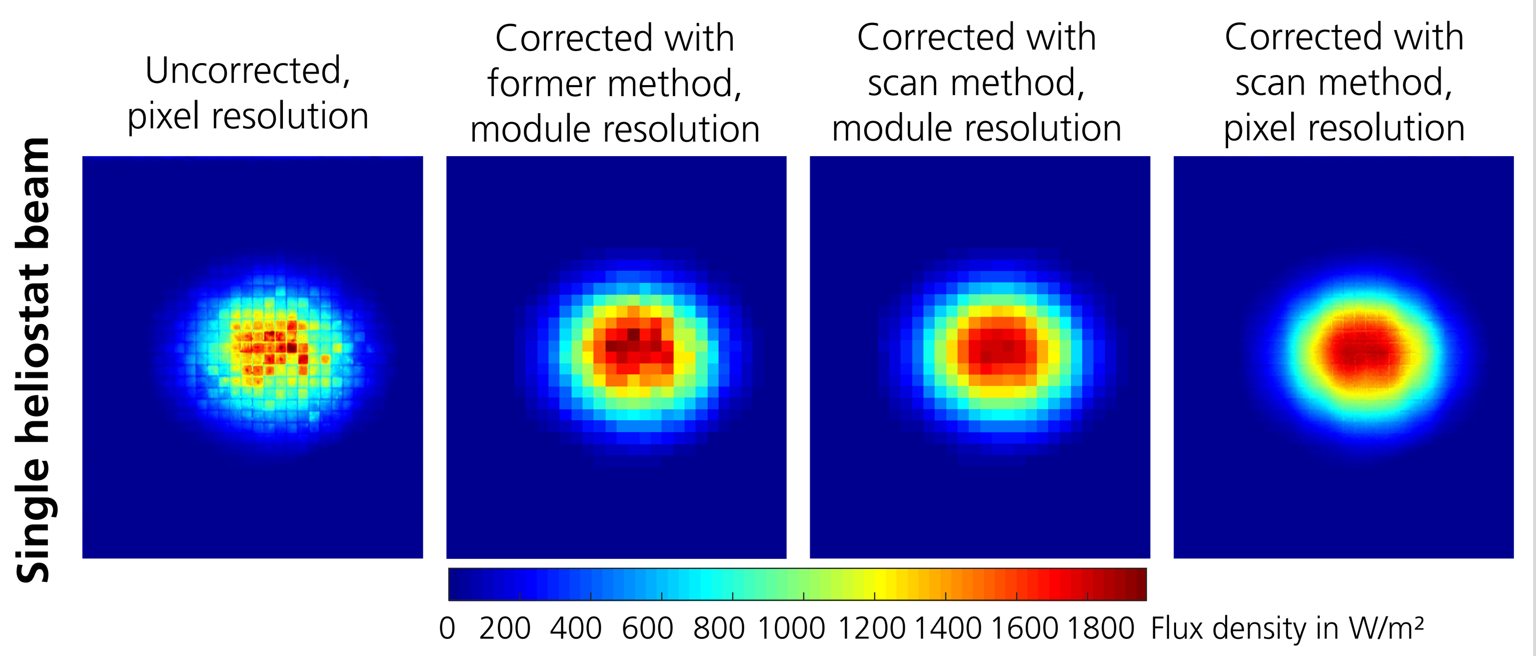
Results

- BRDF f_r (bidirectional reflectance distribution function) of entire absorber surface was determined in situ at plant.
- Strong dependence of reflectance on direction of irradiation observed (factor ~3 between extremes)
- Retroreflective behavior of open volumetric receiver recognizable

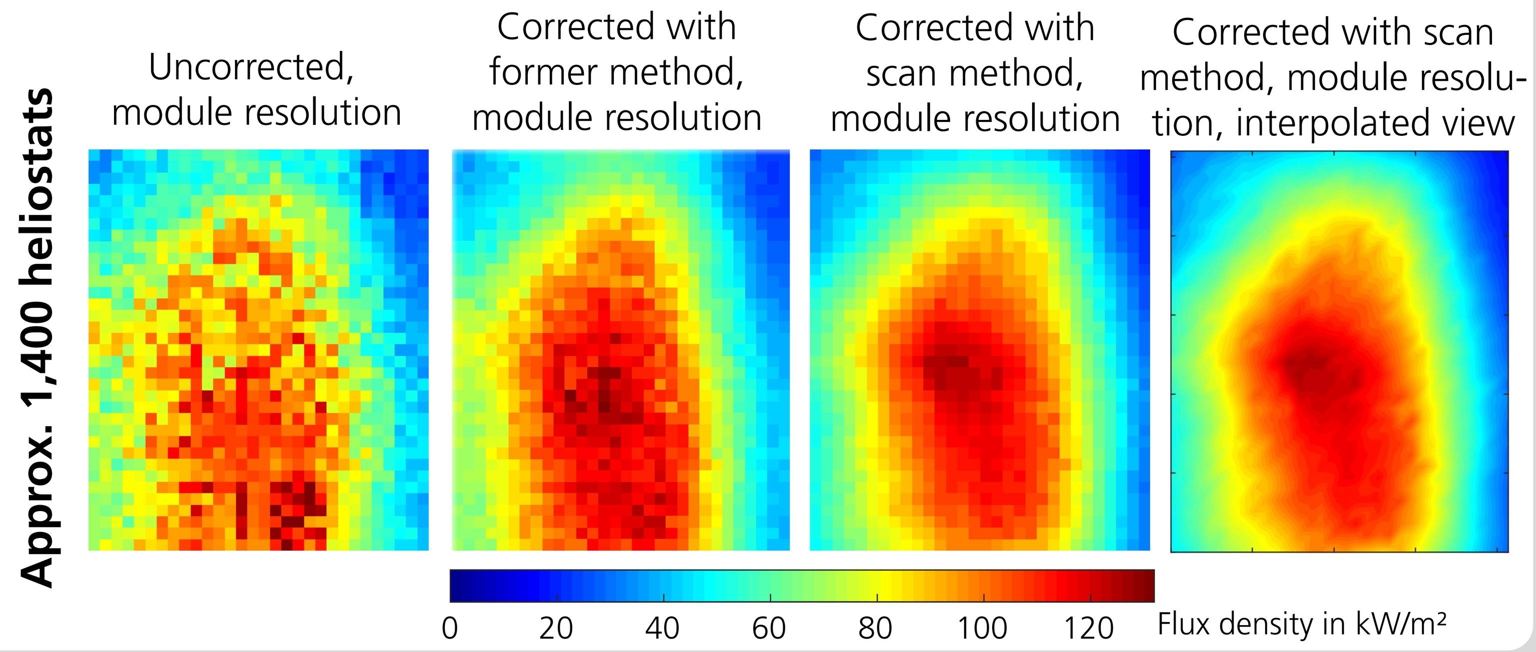


Absorber module at eastern end **Absorber module at western end**

- Significant smoothing of measured flux density distribution by scan method (compared to former method)
- Reason: Local differences in directional dependency are taken into account



- Good correction results in joints between absorber modules suggest suitability for tube receivers, too.
- Plausibility check of radiant flux results using CFD receiver model shows fine agreement.



Summary & Outlook

Key results

- Stringent mathematical formulation of method
- Invention of new approach for reflectance correction ("scan method"). Innovations for detection of directional composition and calibration.
  Tests at Solar Tower Juelich.
- Advantages of new "scan method" over formerly used reflectance correction method:
  - Detection of directional dependency for entire absorber surface in situ at plant
    ⇒ smoother flux density results
  - Irradiation of absorber is more even.
  - Spectra are more similar to measurement.

⇒ Promising for commercial applications at large-scale receivers including tube receivers. German patent [3].

Ongoing and future work

- Completion of measurement uncertainty analysis
- Validation using radiometers
- Scans with spotlight at night
- Transfer to tube receiver with experimental proof
- New research project has started.

References

(1) Röger et al., "Techniques to Measure Solar Flux Density Distribution on Large-Scale Receivers", J. Sol. Energy Eng., 136(3), 031013 (2014)
(2) Ho et al., "A Photographic Flux Mapping Method for Concentrating Solar Collectors and Receivers", J. Sol. Energy Eng., 134(4), 041004 (2012)
(3) Offergeld et al., German Patent 10 2016 226 033 (2016)
(4) Offergeld et al., "Flux Density Measurement for Industrial-Scale Solar Power Towers Using the Reflection off the Absorber", AIP Conf. Proc. 2126, 110002 (2019)

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